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DETECTING PRIMARY SIGNALS USING TIME AND SPACE MODEL (PREPRINT)

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14. ABSTRACT
The advantage of using cognitive radio technology is its ability to adapt and behave to the needs of the application. The adaptability to the application leads cognitive radios with the potential for creating next generation cognitive wireless network. In dynamic spectrum allocation problem, the cognitive radio technology is used to detect the presence of primary user signal so that spectrum will be efficiently utilized by cognitive users (secondary users). To detect the presence of primary user, cognitive radio requires the data related to history of primary signal including time, signal strength (signal will be detected above certain threshold) through detection techniques (energy detectors, matched filter, feature detection, etc.), and finally analyze this data to detect the signal without failure. In this research, a stochastic model is used to detect the primary signal at a given time and space (primary signal decodable area or domain). The proposed time-space model uses Drake's equation to improve the detection of primary signal.

15. SUBJECT TERMS
cognitive radio, primary signal, Drake equation, probability, energy detector

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Detecting Primary Signals Using Time and Space Model

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Abstract

The advantage of using cognitive radio technology is its ability to adapt and behave to the needs of the application. The adaptability to the application leads cognitive radios with the potential for creating next generation cognitive wireless network. In dynamic spectrum allocation problem, the cognitive radio technology is used to detect the presence of primary user signal so that spectrum will be efficiently utilized by cognitive users (secondary users). To detect the presence of primary user, cognitive radio requires the data related to history of primary signal including time, signal strength (signal will be detected above certain threshold) through detection techniques (energy detectors, matched filter, feature detection, etc.), and finally analyze this data to detect the signal without failure. In this research, a stochastic model is used to detect the primary signal at a given time and space (primary signal decodable area or domain). The proposed time-space model uses Drake's equation to improve the detection of primary signal.

Keywords: cognitive radio, primary signal, Drake equation, probability, energy detector

1. Introduction

Mitola [1, 2] described an adaptive radio which adjusts its operation based on information captured from the environment and measurements of its own performance. The adaptive radio named as cognitive radio (CR), plays the role of sharing the spectrum by multiple users through adaptive mechanisms that distinguish users in terms of time, frequency, code, and other signal characteristics. Currently, CR requires computationally efficient and self evolving cognitive models where their behaviors change with changing environment.

The cognitive cycle of the cognitive radio, defined by Mitola [1], contains various states such as observe, learn, plan, decide, and act. The output of the cycle then translates to settings for various 'knobs' that control the wireless system's behavior in a given wireless channel. The system uses simple if-then-else rules, the most commonly used AI (artificial intelligence) techniques, and typically uncontrollable to work within a set of operational constraints. The system may use neural networks, but neural network models require extensive training to replicate observed behavior and usually in unexpected ways when presented with a totally new problem. In other words, stochastic models or biologically inspired cognitive models address the traditional short comings of most of the AI models. The study of self evolving cognitive models whose behavior changes with environment is in its primitive level.

Ideal spectrum sensing helps the cognitive radio (CR) user to make correct decision of utilizing unused spectrum efficiently. Spectrum sensing is the detection of the primary user (PU) in the frequency band of interest and helps to assign the CR user in the absence of primary user. Various techniques are used to detect the presence of PU. In most of the cases, the CRs use the help of energy detectors (ED) to detect the presence of PU in the spectrum space. It is also possible that CRs may determine the geographical information (current status) of the PU. The research shows that the geographical information of the PU could be done better using the collaborative communication in the cognitive radio networks [3, 4, 5]. Various spectrum sensing techniques were discussed by Kataria [6] including collaborative strategies to solve the spectrum sensing problem.

Cognitive radio is considered as spectrum sharing technology and concentrates on spectrum holes without overlapping the primary user signal. For efficient utilization of spectrum holes, the CR must sense the spectrum segments and adapt to use spectrum segments without interference with PU. The physical layer signal structure helps for such flexible operations including power sensing and waveform sensing. The physical layer issues of wide-band CR systems was studied by Tang [7] and suggested that OFDM (orthogonal frequency division multiplexing) is the best physical layer candidate for wide-band CR systems. Further, Dietterich [8] discussed the machine learning techniques in cognitive networks and their influence for the better performance. The panel session of CROWNCOM 2006 [9] on 'Autonomic Communications and Wireless Cognitive Networks' concluded that the cross layer optimization is likely to bring the most benefits by exploring the environmental awareness and that intelligence/cognition should go first in, to produce the highest return on investment.

Cognitive radio design poses more implementation challenges since it requires ability to sense the spectral environment and flexibility to adapt transmission parameters. The design of CR must detect the weak signals and very strong signals. The solution may include the

adaptive notch filtering (similar to ultra wide band designs), banks of on chip radio frequency (RF) filters possibly using Micro-Electro-Mechanical Systems (MEMS) technology such as film-bulk-acoustic-resonator (FBAR), and spatial filtering RF beam-forming through adaptive antenna arrays [10]. The implementation issues in spectrum sensing for CRs are briefly discussed by Cabric [18]. The implementation challenges include a cognitive network where a primary transmitter communicates with primary receivers within the primary exclusive region. The cognitive user transmits and receives outside the guard area of the primary user. Vu [19] discussed the primary exclusive region radius where PUs can transmit safely and where the guard band size protects the primary users from cognitive users. These bounds can help in design of cognitive networks with primary exclusive regions.

The remaining part of the paper is organized as follows. Section 2 describes the primary signal detection techniques and section 3 formulates the problem. The problem formulation includes the time and space model, explanation of the Drake's equation, and the stochastic model for efficient signal detection. Section 4 discusses the simulations of the problem and section 5 presents the findings and conclusions.

2. Primary Signal Detection Techniques

The cognitive radio improves the spectrum utilization significantly by quickly detecting the specific spectrum holes (unused spectrum) and switching rapidly for utilization of unused spectrum. This action may introduce the interference in primary users and disturb the quality of service. So the CR should be able to adapt the spectrum conditions flexibly. In order to avoid the harmful interference to the primary signals, the CR needs to sense the availability of the spectrum. The goal of the spectrum sensing is to decide whether the primary signal is present. The detection of the primary signal will be done by using an energy detecting hardware; otherwise, the CR must be able to determine the exact geographical information (location) of the primary user. The following are some of the approaches to detect the presence of a PU.

Energy detectors (ED) measures the energy through signal strength indicator in the input wave over a specific interval. The primary signal is sensed if the energy in the channel is above certain threshold value. But the false detection of primary signal may happen due to the presence of noise, low energy signal or other secondary users with whom it needs to share the spectrum. Regardless of the detection scheme, the front-end architecture consists of RF amplifier, filter, and a bank of local oscillators (LO) each tuned such that the desired incoming LO leakage signal will fall into a fixed intermediate frequency (IF) band, where the signal would be sent to the detection circuitry [12]. One detector would be implemented for each channel that the node is supervising.

There are several drawbacks of using ED. The in-band interference confuses the energy detector even if the threshold is set adaptively. Many times the energy detector does not differentiate between modulated signals, noise, and interference. Since the spectrum policy for using band only constrained to PUs, the CR should treat noise and other secondary users differently. Further, the ED does not work for spread spectrum signals, direct sequence and frequency hopping signals. So more sophisticated signal processing algorithms need to be implemented.

This concludes that the PU detection using ED will be done better by looking into foot prints of primary user signals (modulation type, data rate and/or various other signal features).

Matched Filter maximizes received signal-to-noise ratio. It requires a dedicated receiver for every PU class. In matched filter, the CR has priori knowledge of PU signal at both physical layer and medium access control (MAC) layers (modulation type and order, pulse shaping, packet format, etc). The main advantage of matched filter is that due to coherency, it requires less time to achieve high processing gain since only samples are needed to meet a given probability of detection constraint [16].

Feature detection helps to detect the presence of weak signals and is normally used in military operations. In this approach the wireless device uses cyclostationary signal processing to detect the presence of primary signals. The cyclostationary signals normally involve the operations such as sampling, scanning and modulation. The cyclostationary signals exhibit correlation between widely separated spectral components due to spectral redundancy caused by periodicity [17]. The procedure of detection may fail due to shadowing or fading effects.

Cooperative spectrum sensing will help for better spectrum sensing. When cognitive radio is suffering from shadowing by a high building over the sensing channel then multiple cognitive radios can be coordinated to perform the spectrum sensing cooperatively [3, 4, 5]. The cooperative technologies in cognitive networks are broadly categorized into three categories: (a) decentralized uncoordinated techniques, (b) centralized coordinated techniques, and (c) decentralized coordinated techniques. Among these techniques, the centralized coordinated and decentralized coordinated techniques perform better and further decentralized coordinated techniques have less overhead.

In addition to these techniques, there are many hybrid techniques used to detect the primary user for efficient utilization of unused spectrum. One of the models discussed by Martinez [13] uses more than one user that cooperates to detect the primary user entry and exit. The

results conclude that the cooperation helps to minimize the false alarms. Gudmundson [14] proposed an auto correction model for the received signal in shadow fading in a mobile radio system. The results show that model is a good fit for moderate and large cells but in microcellular environments, the signal is contaminated with multipath fading and the results are less accurate.

The technique used in this paper is a combination of energy detector data and feature detector data which helps to detect the weak signals and minimize the false detection of primary signals. In the following sections, we used simulations of the energy detector data with space-time model and then used the stochastic model for efficient detection of the primary signals. The model is formulated in the next section.

3. Problem Formulation

3.1 Status of signal

The detection of PU is done by energy detectors at transmitting (transmitter detection) and receiving (receiver detection). The energy detector is called the LO and the RF is sensed through LO leakage power which is at the front end of primary receivers [12]. The detection ensures that CR will not interfere with the primary user. A single LO consists of RF amplifier, filter, and a local oscillator. The LO is tuned to LO leakage signal connected to a fixed IF filter band which then sends to detection circuitry. The detection of LO will be notified to CR to end the channel usage. The primary user enters at any time and transmitting or receiving space.

It is necessary to define a strictly defined volume of space in which primary signals are strong enough to be picked up. The energy detector space closer to the radio receiver must be close enough to detect the PU signal. If we receive a short and random signal closer to PU signal, it may be a random PU communication. But the random PU communication may misunderstand with the noise generated by secondary user signals during the absence of PU signal. Hence it is important to find the status of the primary signal at any given time. The status of the primary signal at any given time is the ratio of average time of communication of primary signal time over duration of communication time (total communication time), which is always less than or equal 1 and greater than or equal to 0. Therefore the status of primary signal f_t at any time t is given by

$$f_t = (t_a / t_d) \in [0,1] \qquad \text{--- (1)}$$

Where, t_a is average time of communication of primary signal time and t_d is duration of communication time (total communication time)

With limited sensitivity of our devices appointed by CRs, signals emanating from primary receivers could only be detected within a certain radius around the primary transmitter. We know that reduction of electromagnetic signal strength is directly proportional to the square of the distance traveled [11]. But the radio receiver is never 100% perfect (technical impossibility) and the receivers never receive infinitely weak signals. The statement concludes that the area where primary signal is detectable (V_{pd}) is finite and influences the probability of primary signal detection. But the volume of the space that primary signal exists (V_{pe}) influences the probability of primary signal detection. Since V_{pd} and V_{pe} are defined in the volume and their existence is related to volume of spear. Therefore, the volume ratio f_v (the ratio between signal detectable and signal existence) is given by

$$f_v = (V_{pd} / V_{pe}) \in [0,1]$$

$$f_v = (r_{pd}^3 / r_{pe}^3) \in [0,1] \qquad \text{--- (2)}$$

where, $V_{pd} = (4/3)\pi r_{pd}^3$, $V_{pe} = (4/3)\pi r_{pd}^3$, and

r = radius of primary user decodable space. The volume ratio f_v describes the probability that the primary signals are close enough to the cognitive network that the primary signals can be detected with our cognitive radios. The situation is similar to the solar system with alien civilization where the alien signals are detectable by our radio systems if they are within our earth's communication range. The grand question of number of civilizations in the galaxy was reduced to seven smaller issues with Drake's view. The Drake's equation is briefly explained by substituting the current situation as part of the problem.

3.2 Drake equation

Let N_{ac} be the primary signals that occupy the spectrum space at any time and can be detected (if they are within the range of energy detectors of our CRs). If they are outside the range our energy detector appointed by the CRs, the signals can not be detected. At any time, we can observe the presence of signals: none, few, or more. The value of N_{ac} is calculated with the well known Drake equation [15]

$$\mathbf{N_{ac} = R^* f_p n_e f_l f_i f_c L} \qquad \text{--- (3)}$$

The variables in the above equation may be interpreted in the current situation as:

R^* = the average rate of PU activation (formation) in the specified spectrum space

f_p = fraction of those PUs that occupied the spectrum

n_e = average number of PUs that are potentially supported by spectrum

f_l = fraction of those channels that will come in contact of ED (energy detector)

f_i = fraction of those have highly detectable signals

f_c = fraction of those PUs that have detectable signals

L = Length of time the primary signals release detectable signals

Note that the number of currently available primary signals N_{ac} has integer value and normally greater than or equal to 1. Better detection will be available by having higher value for N_{ac}. If 60% of primary signals occupy the spectrum, then sum of f_l, f_i, f_c must be equal to 60%. If average number of PUs potentially supported by the spectrum is approximately 50% (percentage can vary), then N_{ac} depends upon product of R^* and L. The product of the values of these two variables must be large number so that N_{ac} is greater than 2. For example, let us assume that the value of N_{ac} varies 1 to 100 (it can be more than 100). Then the probability of signal detection will be faster as the value N_{ac} increases. The results are shown in simulations using MATLAB language.

3.3 Detection of Primary signal

Let the probability of receiving a signal (entering into primary signal domain/space at a particular time) from exactly one primary signal is p_r . The probability of receiving a primary signal p_r at receiving domain at a particular time is function of time and space. Hence the probability of receiving a signal from exactly one primary signal is:

$$p_r = K * f_t * f_v \qquad \text{--- (4)}$$

where, $0 \le K \le 1$ is a constant multiplier (detection threshold factor). The constant value will be adjusted depends upon the time that signal is communicated (the value close to 1, if the signal communicated enough to detect). The time ratio f_t and volume ratio f_v are defined in equations (1) and (2).

In equation (4), the value of p_r provides that a primary signal is somewhere within the primary signal receiving domain. Here we consider all the primary signals that are transmitting at the same time. The interpretation is:

- If exactly one primary signal is in our CRs communication range, then we shall certainly have an opportunity to detect it sometime during the existence of our transmission.

The probability of the signal that we never detect is:

$$p_{nd} = 1 - p_r \qquad \text{--- (5)}$$

Using the equation (5) we can calculate the probability p_{ndp} that we will never detect signals from primary signal space (for all signals). For this we simply have to repeat the stochastic event p_{nd} with N_{ac} times.

$$p_{ndp} = p_{nd} * p_{nd} \ldots * p_{nd} \, (N_{ac} times)$$

The above equation simplifies to

$$p_{ndp} = p_{nd}^{N_{ac}} \qquad \text{--- (6)}$$

Since p_{nd} is less than 1, p_{ndp} gets smaller when N_{ac} gets bigger (Figure 3 and Figure 4). This is exactly what we expected.

The probability that we never fail to detect even a single primary signal decreases if there are more primary signals that exist in the transmittal space. The decrease (decrease in fail to detect) is exponential. The more primary signals are in area, the less chances to miss the signals.

Hence, the probability of detecting any signal p entering into a domain of primary signal space is given by simply subtracting the signal that never be detected from 1. The value p is calculated as:

$$p = 1 - p_{ndp} \qquad \text{--- (7)}$$

Substituting equations (4), (5), and (6) in (7) we get

$$p = 1 - (1 - K * f_t * f_v)^{N_{ac}} \qquad \text{--- (8)}$$

The above equation provides the probability of detecting the primary signal in the area where primary signals will be decoded. Since the values of f_t and f_v are less than 1 then the product K, f_t and f_v will always less than 1, i.e. $(1 - K * f_t * f_v) < 1$.

Therefore, $(1 - K * f_t * f_v)^{N_{ac}}$ will be a very small quantity as N_{ac} becomes larger.

i.e. $(1 - K * f_t * f_v)^{N_{ac}} << 1 \qquad$ --- (9)

The equation (9) shows that for large value of N_{ac} the value of p is very close to 1. That is, system has high predictably detection of its primary signal.

4. Simulations

The detection of the primary signal depends upon the spectrum space occupied by the primary signals at any given time (N_{ac}). The main factors influence N_{ac} include, average rate of primary user activation in a specified spectrum and length of time the primary signal release detectable. The product of remaining parameters generates very small value and influence negative side. The prediction will be better if the value of N_{ac} would be more than 10.

The Figure 1 is drawn with values for $f_t = 0.1$, $f_v = 0.7$ and for $f_t = 0.2$, $f_v = 0.7$ with variable values of $N_{ac} = 1$ to 70. The figure concludes that quick signal detection requires higher N_{ac} value. Figure 2 is drawn with variation of f_t to detect the signal. The detection of signal was better after four (4) units of time and much better with higher value of N_{ac}. Figures 1 and 2 conclude that N_{ac} has more influence

on detection of primary signal compared to time f_t and volume f_v.

Figures 3 and 4 were drawn to verify the influence of f_t and f_v on detection of primary signal that is fail to detection of signal. The Figures 3 and 4 are drawn for equation (6). The figures show that these parameters have close to same influence on failure to detect the signal. Figure 4 shows that the failure to detect the signal was close to same for values for $f_t = 0.5$, $f_v = 0.5$ and for $f_t = 0.3$, $f_v = 0.8$. These results conclude that detection of primary signal depends upon time and space factors.

5. Conclusions

In the proposed research, we introduced time and space dependent stochastic model to predict the presence of primary signal. Since time and space involved in recognizing the signal, the Drake's equation will be the better choice to use for such situations. The simulations show that the achieving better detection of primary signal depends upon the spectrum space occupied by the primary signal.

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Figures

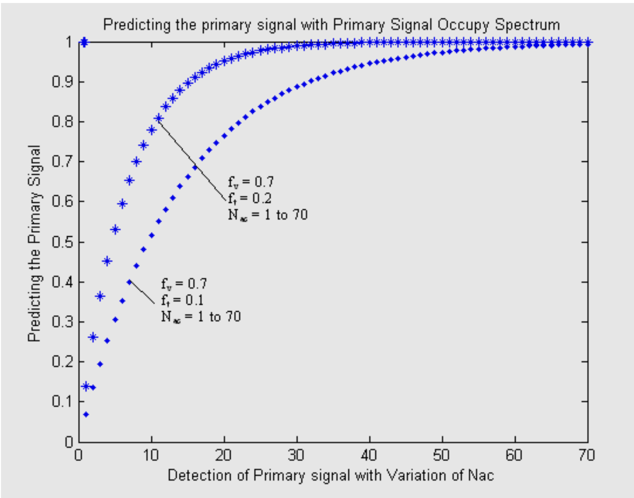

Figure 1: Detection status of primary signal with variant in existing status

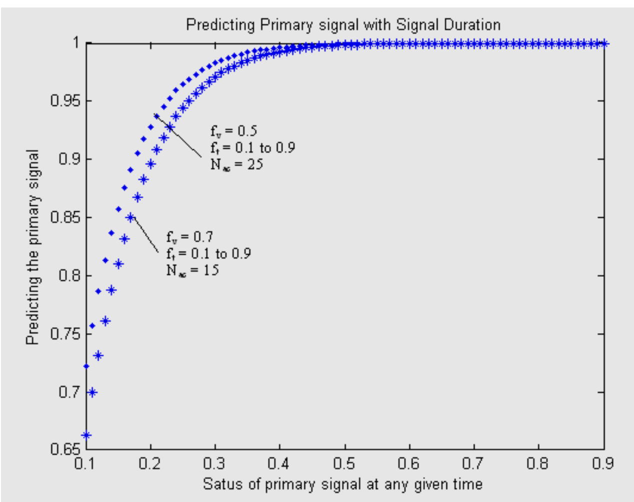

Figure 2: Detection status of primary signal with time duration

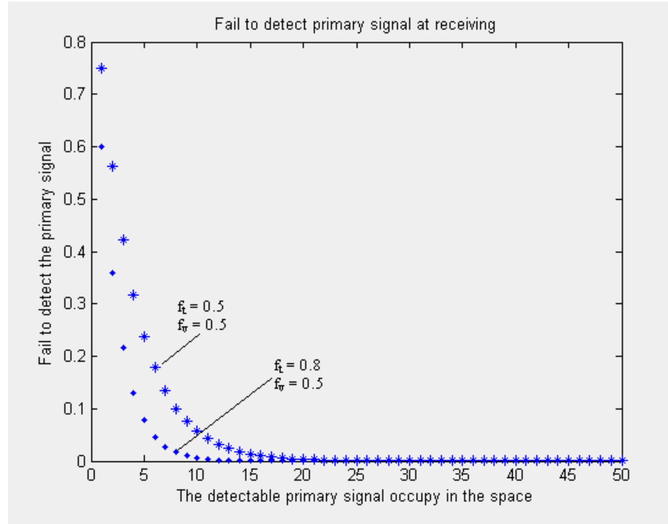

Figure 3: Fail to detect the primary signal at receiving space

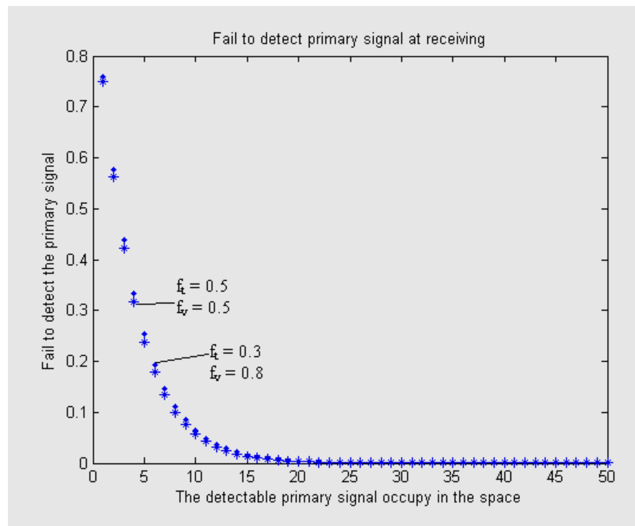

Figure 4: Fail to detect the primary signal at receiving space